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A simple method for predicting radio frequency signal attenuation through a rocket exhaust plume has been developed. A theoretical model development suitable for a writing a computer code to predict line-of-sight RF signal attenuation is presented. The model consists of seven calculation steps: 1. Nozzle exhaust conditions. 2. Correction for non-optimal nozzle expansion. 3. Plume inviscid core flow field. 4. Plume mixing/afterburning region flow field. 5. Plume electron and neutral body density field. 6. Electron-neutral body collision frequency. 7. Radio frequency transmission loss. The model uses many simplifying assumptions and represents the least complex approach available. The model is appropriate only for static-fired motors or low altitude, low Mach number flight profiles.

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A Simple Method for Predicting RF Attenuation Through a Rocket Exhaust Plume

by

L. Glen McMillion

for

U.S. Army Aviation and Missile Command

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CONTENTS

A Simple Method for Predicting RF Attenuation Through a Rocket Exhaust Plume

L. Glen McMillion

Nomenclature:

C_D	=	plume drag coefficient
f	=	exhaust gas mass fraction of total gas in the mixing region
L	=	plume inviscid core length
m	=	mass
M	=	Mach number
MW	=	gas molecular weight
N	=	gas phase chemical species number density, number/cm^3
P	=	pressure
r	=	plume radius
R	=	gas constant
Sc	=	Schmidt number
T	=	temperature
v	=	velocity
x	=	axial (longitudinal) position
y	=	thickness of plasma slab stream
γ	=	gas specific heat ratio (C_p/C_v)
ν	=	electron-neutral body collision frequency
ρ	=	gas density

Subscripts:

CL	=	center line
e	=	nozzle exit
e^-	=	electron
i	=	inviscid core boundary (when used for plume radius, 'r')
i	=	core value if $x \le L$; center line value if $x > L$ (when used for 'u' and 'f')
i	=	index counter on summations (when used with Σ)
j	=	start of pressure-balanced jet (mixing/afterburning region)
s	=	sound
t	=	turbulent
∞	=	free stream

1.0 INTRODUCTION

A theoretical description of the governing mechanisms of attenuation of radio frequency electromagnetic waves through rocket motor exhaust plumes is developed and presented as a simplified mathematical model for prediction of attenuation. This presentation is suitable as the basis for writing a computer code to perform RF signal attenuation predictions.

The existing theory for predicting radar attenuation by absorption applies only to weakly-ionized plasma with uniform properties; the plasma resulting in the exhaust of a typical tactical rocket motor can safely be assumed to be weakly ionized, but cannot be assumed to be uniform throughout. Therefore we must calculate the properties of several adjacent streams, which are referred to as slabs, within the exhaust plume, each having approximately uniform properties, and transversed by the radar beam in a series sequence. The total attenuation is the summation of transmission loss through the adjacent slabs.

Therefore predicting radio frequency transmission loss through a rocket exhaust plume requires that the exhaust plume model provide a description of the spatial variation of temperature and chemical species concentrations. Models of varying degrees of complexity exist. The model presented here represents the least complex approach that has been found to provide reasonably accurate results. This model consists of the following steps:

1. Calculate nozzle exhaust conditions.
2. Calculate correction for non-optimum nozzle expansion.
3. Calculate plume inviscid core flow field.
4. Calculate plume mixing/afterburning region flow field.
5. Calculate plume electron and neutral body density field.
6. Calculate electron-neutral body collision frequency.
7. Calculate radio frequency transmission loss.

2.0 TECHNICAL DISCUSSION

2.1 Nozzle Exhaust Conditions

Nozzle exhaust conditions are calculated using the Naval Weapons Center Propellant Evaluation Program. There are two versions: MicroPEP and PEP93. PEP93 is a newer version and is more user-friendly than MicroPEP. However, the input format for MicroPEP may make it easier to incorporate into a larger exhaust plume RF interaction code. Copies of both programs are included with this report.

Input data required to run PEP to calculate nozzle exhaust conditions are:

1. Propellant formulation. The propellant formulation MUST include concentrations of the alkali metals sodium and potassium. The attenuation of RF signals by rocket exhausts is due to free electrons in the plume, which are formed primarily by ionization of sodium and potassium. Sodium and potassium are not usually present as intentional ingredients but are present as contaminants in other ingredients, particularly ammonium perchlorate. Each ingredient in the formulation must be assayed for sodium and potassium and the total amount of each calculated for the propellant. Any sodium and potassium present as contaminants will be present as positively charged ions, not as the metal. Therefore an ionic species such as sodium chloride or potassium chloride should be chosen from the propellant ingredient list. The weight of each salt to use must be adjusted to account for the weight of the anion (chloride, in this example) while providing the total weight of alkali metal present as calculated from ingredient assays. Note that the amount of alkali metal salts input as propellant ingredients must include the contribution from nozzle throat and exit cone ablation, which is discussed next.

2. Alkali metal mass flow rate during motor operation due to ablation of nozzle throat and exit cone. Nozzle throats and exit cones are usually made of materials that are ablative and that contain sodium and potassium as trace contaminants. The ablation rates must be known so that the mass flow rate of alkali metals introduced into the plume by nozzle ablation can be calculated.

Ablation rates are usually given as millimeters per second or a similar length per unit time value. To calculate the mass flow rate of ablative material the area of ablative material exposed to the combustion gases must be calculated for the nozzle geometry. Alkali metal mass flow rate is then calculated by multiplying the ablative material mass flow rate by the mass fraction of alkali metal in the ablative material. The total amount of alkali metals introduced into the plume during the motor burn is found by multiplying the mass flow rate by the burn time. This number can be treated as an equivalent amount of alkali metals in the propellant. This is how alkali metals due to nozzle ablation should be included in the calculation.

3. Rocket chamber operating pressure.
4. Nozzle expansion ratio.
5. Nozzle exit pressure (ambient pressure).

When running PEP the following options must be selected: the program must be instructed to include ionic species in the calculations, the lower limit of species concentrations must be increased by at least four orders of magnitude (the default limit is 10^{-6}), the density exponent should be unity, and all combustion species used in the calculation should be listed.

Chemical reactions are considered to be frozen through the nozzle expansion rather than assuming that chemical equilibrium is maintained during the expansion process. It has been found that equilibrium chemistry calculations applied to nozzle expansion under-predict trace species concentrations, especially free electron concentration, that are critical to radar attenuation predictions.

2.2 Nozzle Non-Optimal Expansion Correction

When a rocket exhaust nozzle is not optimally expanded resulting in the nozzle exit pressure being not equal to the ambient pressure, a correction is needed to locate the axial distance, x_j, at which pressure equilibration is attained and to determine the maximum or minimum inviscid plume radius, which occurs at the axial location x_j.

For low altitude plumes, if the jet properties (r_e, T_e, P_e) are known at the rocket nozzle exit (calculated here from the NWC MicroPEP code), these may be extrapolated to balanced pressure conditions ($P_j = P_\infty$) assuming conservation of mass, momentum, and energy. In this extrapolation, no mass entrainment is allowed, so that mixing with ambient or free stream air starts only after pressure equilibration is reached.

It is reasonable to assume that for the purposes of mixing model definition, the balanced pressure is reached at about the middle of the first plume wavelength. This may be obtained from (Jarvenin and Hill, 1970):

$$x_j = 0.69\, r_e\, M_e\, (\gamma_e\, P_e/P_\infty)^{0.5} \tag{1}$$

At this axial position, plume velocity, temperature, and radius may be given by (Sukanek, 1976):

$$v_j = v_e\, (1 + \xi) \tag{2}$$

$$T_j = [1 - (\gamma_e - 1)\, \xi\, M_e^2 - 0.5\, (\gamma_e - 1)\, \xi^2\, M_e^2]\, T_e \tag{3}$$

$$r_j = \left[\frac{P_e\, T_j\, v_e}{P_\infty\, T_e\, v_j}\right]^{0.5} r_e \tag{4}$$

where:

$$\xi = \frac{\left[-B + \sqrt{B^2 + 4AC}\right]}{2A} \tag{5}$$

$$A = \gamma_e\, M_e^2 + \beta \left[\frac{\gamma_e - 1}{2}\right] M_e^2 \tag{6}$$

$$B = (\gamma_e - 1)\, \beta\, M_e^2 - \alpha + \gamma_e\, M_e^2 \tag{7}$$

$$C = \alpha + \beta \tag{8}$$

$$\alpha = 1 - \left[\frac{P_\infty}{P_e}\right] \tag{9}$$

$$\beta = 0.5\ \gamma_\infty\ C_D\ M_\infty^2 \tag{10}$$

For low altitude plumes RF attenuation is dominated by the near-field plume, that is, the inviscid and mixing/afterburning regions of the plume. For this case it is reasonable to neglect plume drag resulting in $C_D = 0$ and, consequently, $\beta = 0$. This assumption simplifies the equations to:

$$A = \gamma_e\ M_e^2 \tag{11}$$

$$B = \gamma_e\ M_e^2 - \alpha \tag{12}$$

$$C = \alpha \tag{13}$$

$$\alpha = 1 - \left[\frac{P_\infty}{P_e}\right] \tag{14}$$

$$\beta = 0 \tag{15}$$

Equation (1) is used to find the axial position, x_j, at which the pressure-balanced jet begins. Equation (4) is used to find the jet radius, r_j, at x_j. The jet radius r_j is used as the starting radius for subsequent calculations of jet properties. Equations (2), (3), (5), and (11) to (15) are used to solve equation (4) for r_j.

2.3 Plume Inviscid Core Flow Field

The procedure given in Section 2 above is a simplified means of allowing for under- or over-expansion of the rocket nozzle. Its main effect is to change the scale of the jet; the part of the jet downstream of x_j behaves as if it were produced by a parallel-flow nozzle of radius r_j. The inviscid core and mixing layer scales are accordingly normalized by reference to the radius r_j rather than r_e.

The inviscid core length, L, is assumed to be a function of the Mach number, M_j, on the jet center line at the axial position x_j, and is given by:

$$\frac{L}{r_j} = 2.1\ M_j^2 \tag{16}$$

where r_j is calculated from equation (4).

The Mach number, M_j, is the ratio of the local gas velocity to the local speed of sound;

$$M_j = \frac{v_j}{v_s} \tag{17}$$

The speed of sound, v_s, at x_j must be calculated from the gas properties at x_j:

$$v_s = \left[\frac{\gamma_j\ P_\infty}{\rho_j}\right]^{0.5} \tag{18}$$

The gas density, ρ_j, may be calculated using the ideal gas law, and the gas temperature, pressure, and molecular weight (MW) at x_j :

$$\rho_j = MW\left[\frac{P_j}{R\ T_j}\right] \tag{19}$$

Substituting equation (19) into equation (18) yields:

$$v_s = \left[\frac{\gamma_j P_\infty R T_j}{MW P_j}\right]^{0.5} \tag{20}$$

However, since at x_j the jet pressure is equal to the ambient pressure ($P_j = P_\infty$), equation (20) simplifies to:

$$v_s = \left[\frac{\gamma_j R T_j}{MW}\right]^{0.5} \tag{21}$$

Now the Mach number at x_j can be calculated from equations (2), (3), (17), and (21), given γ_j and MW from MicroPEP calculations. Gas molecular weight and γ can be considered constant throughout the inviscid core without significant error, therefore MW and γ from the MicroPEP exit plane calculations will be used. Once M_j is known the core length L can be calculated from equation (16).

The inviscid core is assumed to be a cone of base radius r_j and height L, so that the generator is given by:

$$\frac{r_i}{r_j} = 1 - \frac{x}{L} \tag{22}$$

2.4 Plume Mixing/Afterburning Region Velocity Flow Field

The gas velocity is assumed to remain constant throughout the core, and is allowed decay on the axis beyond the core inversely with x:

$$\frac{u_{CL}}{u_{core}} = \frac{L}{x} \tag{23}$$

The radial variation of the longitudinal component of velocity in the mixing region is expressed as an exponential function of position:

$$\frac{u}{u_i} = \exp\left[- \left[\frac{r - r_i}{r_{1/2} - r_i} \right]^2 \ln 2 \right] \tag{24}$$

where: $u_i = u_{core}$ if $x \le L$;

$u_i = u_{CL}$ if $x > L$;

$r_i = 0$ if $x > L$;

$r_{1/2}$ = the radial coordinate at which $u = \frac{u_i}{2}$

It can be shown that:

$$u_i^2 \, r_i \, \frac{\sqrt{\pi}}{2a} + \frac{u_i^2}{2a^2} = \frac{u_e^2}{2} \left(r_e^2 - r_i^2 \right) \tag{25}$$

where:

$$a^2 = \frac{2 \ln(2)}{\left(r_{1/2} - r_i \right)^2} \tag{26}$$

Equation (25) is a quadratic in 'a' as given by equation (26) and therefore in $r_{1/2}$. If $x \le L$, then $u_i = u_e$ and $r_{1/2}$ may be expressed in terms of r_i, which is a function of x as given by equation (22). If $x > L$ then $r_i = 0$ and $u_i = u_e \, (L / x)$ so that $r_{1/2}$ may be expressed directly as a function of x. This defines the complete plume flow field.

2.5 Plume Electron Density and Neutral Body Field

A rigorous determination of the electron density field requires knowledge of the gas temperature, chemical composition and chemical reaction rates. This means that an exact solution would be undesirably complex in the context of a "simple" model. Therefore a compromise between frozen and equilibrium chemistry with respect to electron density distribution will be

used. If the chemistry of the plume downstream of the nozzle exit plane is assumed to be frozen the plume must behave in all respects as a simple jet of heated inert gas. Under this assumption the mass fraction 'f' of initial exhaust gas per unit mass of total gas (exhaust gas plus entrained free stream air) in the mixing region is described by observed empirical relationships. The mass fraction of exhaust gas to total gas in the plume mixing region is defined as:

$$f = \frac{m_e}{m_e + m_\infty} \tag{27}$$

The exhaust gas concentration on the plume axis has been found to vary as x^{-2} and the radial profile of exhaust gas concentration is governed by the similarity relation:

$$\frac{f}{f_i} = \left[\frac{u}{u_i}\right]^{Sc_t} \tag{28}$$

where:

$$f_i = f_{core} \quad if \quad x \le L;$$
$$f_i = f_{CL} \quad if \quad x > L.$$

The first step in determining the electron density distribution in the model is to assume that the mixing region geometry is defined by the velocity flow field presented in the previous section and that the pre-combustion composition of the gas mixture is described by the variation of 'f' with position. Equation (28) is assumed also to apply to combusting systems and the turbulent Schmidt number is assumed to be unity. These simplifications really mean that we are assuming instantaneous mixing of the exhaust gas with air within the confines of the velocity field. The value of 'f' at any point is given by:

$$f = 1 \quad inside\ the\ core \tag{29}$$

$$f = f_i \exp\left[-\left[\frac{r - r_i}{r_{\frac{1}{2}} - r_i}\right]^2 \ln(2)\right] \tag{30}$$

$$f_i = 1 \quad for \quad x \le L \; ; \; f_i = \frac{L^2}{x^2} \quad for \quad x > L. \qquad (31)$$

Having in this way specified a mixture composition at all points within the mixing region, the effects of secondary combustion and heat release are simulated by permitting instantaneous reaction to chemical equilibrium.

Plume mixing region chemical equilibrium calculations are performed using the NWC MicroPEP or PEP93 code; by using the appropriate switches PEP will perform chemical equilibrium calculations of any type. For MicroPEP this option is selected by entering a "1" in the seventh space of the fourth line of the input file and replacing the chamber pressure with the desired temperature on the Final Lines of the input file (see the "readme.txt" file included on the MicroPEP diskette). The input for performing this calculation consists of the chemical composition of the exit plane exhaust gas and the temperature of the mixed plume gas (before allowing for chemical reaction) as determined by mixing the exhaust gas with freestream air at the ratio, 'f', calculated from equations (29), (30), or (31). This is a simple trial and error calculation which finds the temperature of the mixed exhaust gas and air by matching the enthalpy lost *by* the exhaust gas *to* the air with the enthalpy gained *by* the air *from* the exhaust gas during the mixing process. The constant-pressure heat capacity as a function of temperature, $C_p(T)$, must be known for air and the exhaust gas over the temperature range of interest. The heat capacity of the exhaust gas must be calculated from the heat capacities of the individual component species and their mole or mass fractions, depending on the units of the C_p data used. The heat capacity of air is tabulated in many sources in the open literature. Once the temperature (before allowing for chemical reaction) and composition of the mixed plume gas are known, PEP is run to calculate equilibrium composition and enthalpy released by the chemical reactions. The equilibrium composition includes free electrons and the neutral bodies that will be required to calculate collision frequency in Section 2.6. The final temperature of the mixed, reacted gas is calculated by dividing the enthalpy of reaction by the constant-pressure heat capacity of the mixed gas to find the temperature increase due to reaction and adding this value to the non-reacted temperature of the system.

For this simple model, enthalpy changes due to changes in momentum (mixing and velocity changes) are considered to be negligible with respect to static enthalpy of the exhaust gas and free stream air. If evaluation of the use of the model indicates that conservation of momentum is significant, the relationships presented by A. C. Victor, NWC TP 5319, Part 1, Section 2.2, page 11-13 should be used (Victor, 1975).

2.6 Electron-Neutral Body Collision Frequency

The electron-neutral body collision frequency at any point in the plume is calculated from (Cummings, Williams and Wilson, 1970):

$$\nu = \nu_{e^-} \Sigma_{i=1}^{m} (N_i \, q_i) \qquad (32)$$

where:

$$\nu_{e^-} = \sqrt{\frac{8kT}{\pi \, m_{e^-}}} = \textit{mean thermal electron velocity, where:} \qquad (33)$$

k = *Boltzmann constant* = 1.38066×10^{-23} *J* K^{-1}

T = *temperature as degrees Kelvin* (*K*)

m_{e^-} = *electron mass* = 9.10953×10^{-28} *gram*

N_i = *number density of species i*

q_i = *electron collision cross-section of species i*

In practice, only a few of the species present in the exhaust gases have collision cross-sections large enough to contribute significantly to the collision frequency. These are typically H_2, H_2O, N_2, CO, and CO_2. The contribution to collision frequency by all other species is neglected in this model. Thus the calculation of the equilibrium composition and temperature in the mixing region serves as the basis for determining collision frequency.

Electron-neutral body collision cross-sections are dependent upon the electron velocity, v_{e^-}. The electron-velocity-dependent collision cross-sections in the c.g.s. system of units for H_2, H_2O, N_2, CO, and CO_2 are given in Table 1 (Smoot and Underwood, 1966):

Table 1.

Collision Cross-Sections of Electrons with Neutral Species

Species	Cross-Section, q_i (c.g.s units)
H_2:	$1.45^{-23}\ v_{e^-} + 8.9^{-16}$
H_2O:	$5.9\ v_{e^-}^{-2}$
N_2:	$3.29^{-23}\ v_{e^-}$
CO:	$2.08^{-23}\ v_{e^-} + 2.46^{-16}$
CO_2:	$4.7^{-8}\ v_{e^-}^{-1}$

2.7 Radio Frequency Signal Transmission Loss

A knowledge of N_{e^-}, ν, and radar frequency, ω, is sufficient to allow a direct prediction of radar attenuation. The existing theory for predicting radar attenuation by absorption applies only to weakly-ionized plasma with uniform properties; the plasma resulting in the exhaust of a typical tactical rocket motor can safely be assumed to be weakly ionized, but cannot be assumed to be uniform throughout. Therefore we must calculate the properties of several adjacent streams, which are referred to as slabs, within the exhaust plume, each having approximately uniform properties, and transversed by the radar beam in a series sequence. The total attenuation is the summation of transmission loss through the adjacent slabs, each of thickness y_i :

$$db = 0.46 \sum_{i=1}^{m} \left[\frac{y_i\ \nu_i\ (N_{e^-})_i}{\nu_i^2 + \omega^2} \right] \qquad (34)$$

Equation (34) has been used to predict X-band and K-band radar transmission loss for two solid rocket propellants (Smoot and Underwood, 1966).

3.0 SUMMARY AND RECOMMENDATIONS

Classified and unclassified literature was searched for articles and reports about methods for predicting radio frequency signal transmission loss through rocket motor exhaust plumes. The resulting literature was examined and evaluated to create a simple yet effective prediction methodology. A great deal of the literature deals with very complex methods or rocket flight profiles that are of no interest to this project. No single article or report presented a method that could be applied to this project; many articles had to be drawn upon and scrutinized to create the prediction method presented in this report. The resulting method is based upon simplifying assumptions that are specific to low altitude, low Mach number flight profiles and propellants that are suitable for tactical missiles. The equations describing rocket exhaust plume velocity fields, chemical and physical properties, and the interaction of radio frequency signals with exhaust plume plasmas have been described and organized in a way that can be used to write a computer code to calculate line-of-sight RF signal attenuation through an exhaust plume.

All of the effort to date has been spent on analyzing the available methodologies and creating a suitable methodology for this project based on appropriate simplifying assumptions (Phase I); the work presented in this report required greater effort than anticipated and a second phase (Phase II) will be required to complete the project as described in the Statement of Work.

This report presents the results of Phase I: the complete theoretical description required to write a computer code for predicting RF transmission loss through rocket exhaust plumes. Computer programming for Phase II will use FORTRAN or ANSI C programming language at the direction of the customer. The estimated effort to perform Phase II of this task is:

a.	Type of Contract:	Time and Materials
b.	Number of Days:	340
c.	Labor Rate:	$310.00/day
d.	Cost of Labor:	$105,400.00
e.	Cost of Materials:	$ 3,000.00
f.	Total Estimated Cost:	$108,400.00

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